Agricultural Water Management 98 (2010) 314–320

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Hydro-physical characteristics of selected media used for containerized agriculture systems

Vivek Kumar[a], Felipe M. Guerrero[a], Berrin Tansel[a,*], M. Reza Savabi[b]

[a] Florida International University, Civil and Environmental Engineering Department, 10555 West Flagler Street, Engineering Center Miami, FL 33174, United States
[b] United States Department of Agriculture, ARS, Miami, FL, United States

ARTICLE INFO

Article history:
Received 20 November 2009
Accepted 30 August 2010
Available online 15 October 2010

Keywords:
Nurseries
Water infiltration
Best management practices
Water retention
Particle size distribution
Containerized agriculture systems
Soil–water interactions

ABSTRACT

Containerized plant production represents an extremely intensive agricultural practice with large amounts of moisture and fertilizer application. Hydro-physical characteristics such as water infiltration, texture and structure, particle size distribution affect the quality of the media used in containerized agricultural systems and the water availability to plants. Water retention characteristics depend on particle size distribution as well as the composition of the media used. Materials with coarser particles allow faster percolation of water and also retain relatively higher amounts moisture per unit weight due to higher porosity, while draining faster due to smaller surface area per unit weight. Faster drainage can result into airflow through coarser materials causing the media to dry. The objectives of this study were to characterize the selected hydro-physical properties of plant growth media that are commonly used by nurseries in South Florida. Characterization of the plant growing media can allow modeling of soil–water interactions and development of best management practices for more efficient use of water and agrochemicals by nurseries. Experimental analyses were performed to characterize the plant growth mixtures in terms of particle size distribution and hydraulic conductivity using three different methods (i.e., constant head permeability, falling head permeability test, and tension infiltrometer test). The saturated hydraulic conductivity of the mixtures measured by constant head method ranged from 0.029 to 0.042 cm/s (104–151 cm/h) and by falling head method ranged from 0.078 to 0.112 cm/s (281–403 cm/h). The saturated hydraulic conductivity of the mixtures measured by tension infiltrometer ranged from 0.02 to 0.34 cm/h. Understanding water retention and permeation characteristics of the plant growing media could assist development of best management practices (BMP) for containerized agricultural systems for efficient management of irrigation water and agrochemical use.

1. Introduction

Florida is the second leading horticulture state in the United States with greenhouse/nursery sales of more than $1.6 billion annually. Containerized plant production represents an extremely intensive agricultural practice with large amounts of water and chemical fertilizer use. Considering that three national parks (Everglades, Biscayne and Big Cypress) in South Florida surround the agricultural areas where containerized agricultural systems are used, there exists a major challenge for development of effective practices that combine maximizing crop production while reducing the quantities of agrochemicals released to the environments by runoff. Non-point source pollutants (i.e., nutrients, pesticides, and other chemicals) originating from agricultural areas have been implicated as a source of water quality degradation in southern Biscayne Bay (FFR, 1999). Nutrient loadings to Everglades, Biscayne Bay and Big Cypress National are an environmental concern due to high sensitivity of the ecosystem to eutrophication. The nutrient loads from agricultural and urban areas have significantly increased nutrient concentrations, particularly phosphorus in surface waters. In addition, discharging phosphorus at the current control target of 50 μg/L would continue to allow eutrophication of over 95% of the Everglades marshes (USEPA, 1998).

Farming methods can alter soil properties such as soil structure, porosity, as well as the hydraulic conductivity and water retention. In South Florida, transition to containerized agricultural practices is driven by market demands and production advantages including higher production per acre, faster plant growth, higher plant quality, and lack of dependence on arable land (Colangelo and Brand, 2001). In agriculture systems, environmental conditions affect the

* Corresponding author. Tel.: +1 305 348 2928; fax: +1 305 348 2802.
E-mail address: tanselb@fiu.edu (B. Tansel).

0378-3774/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2010.08.023

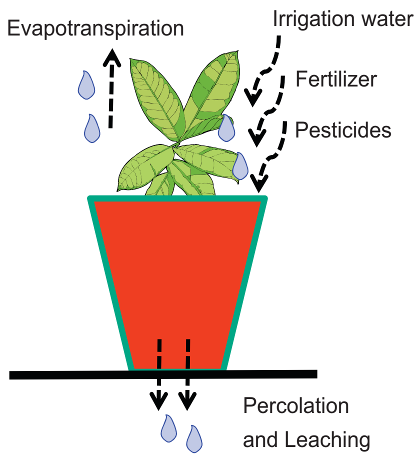

Fig. 1. Important soil–water interactions which affect the water and nutrient management practices.

longevity of fertilizer availability and its release. Because environmental conditions fluctuate, regular monitoring of the nutrient levels is essential to ensure fast plant growth and plant quality. Lack of essential elements will result in slow plant growth and aesthetically unacceptable plants. Conversely, excessive nutrient concentrations result in root injury, hindering the plant's ability to absorb water and nutrients; which also increases the potential for environmental contamination due to excess nutrients (Water Quality Handbook for Nurseries, 1998). Leaching of nutrients is a major concern in agricultural areas. The ability of soils to hold nutrients depends on the mechanics and dynamics of soil–water interactions which affect the nutrient transport as illustrated in Fig. 1. The extent of leaching directly depends on the hydro-physical properties of the plant growing media (i.e., soil or plant mix). The leaching is substantially reduced when the hydraulic conductivity of media is lowered for a stabilized soil and substantially increases when the hydraulic conductivity is increased (Rao and Matthew, 1995). In fine grained soils, the hydraulic conductivity under saturated conditions is controlled by the microstructure of the soil matrix which in turn depends on the type of the fine material (e.g., clay mineral) present in the soil, the composition of the exchangeable cations, and the electrolyte concentration in the pore water system (Rao and Matthew, 1995; Ruth, 1946; Wu et al., 1990; Ndiaye et al., 2007). The measured permeability coefficient at a given porosity is significantly dependent upon the nature of the permeating medium. For example, clays are much more permeable to gases and most organic liquids than to watefr.

It has long been recognized that hydraulic conductivity is related to the grain-size distribution of granular porous media (Freeze and Cherry, 1979; Savabi, 2001). Knowledge of saturated hydraulic conductivity of soil is necessary for modeling the water flow in the soil media (both in the saturated and unsaturated zones) and for modeling transport of water-soluble pollutants. For example, the Everglades Agro Hydrology Model (EAHM) simulates the effects of a range of environmental conditions as well as conditions which can be controlled (i.e., nutrient additions) on the water balance and runoff water quality (Savabi et al., 2005, 2008). Permeability is the ease with which water flows through a soil medium. There are several methods to determine saturated hydraulic conductivities of soils (Savabi, 2001). The two commonly used methods include constant head permeability test and falling head permeability tests. For unsaturated soils, tension infiltrometer can be used to measure the unsaturated hydraulic properties of a soil sample using different tension conditions. During the tension infiltrometer tests, water is allowed to infiltrate the soil at a rate which is lower than the free fall rate of water through a column, accomplished by maintaining a negative pressure on the water. When similar infiltration experiments involving two different negative pressures are performed, the saturated hydraulic properties of the soil can be estimated. One run yields a value for the saturated hydraulic conductivity, which includes the error due to the tension of the negative pressure. If the same experiment is performed keeping all the parameter same as except the negative pressure, a new value for saturated hydraulic conductivity is obtained. The variation of hydraulic conductivity in relation to tension allows estimation of a correction factor can be corrected by using the correction factor in relation to tension (Whal, 2004). Water retention characteristics of soils with coarse texture are more sensitive to the amount of organic carbon in comparison to fine-textured soils. Water retention depends on the proportion of textural components and the amount of organic carbon in the soils. For coarse soils with low carbon content, increase in carbon content results in increase in water retention. However, for fine-textured soils, increase in carbon content results in decrease in water retention (Rawls et al., 2003).

The objectives of this study were to characterize the selected hydro-physical properties of plant growth media that are commonly used by the nurseries in South Florida. Characterization of the plant growing media can allow modeling of soil–water interactions and development of best management practices for more efficient use of water and agrochemicals by nurseries. Experimental analyses were performed to characterize the plant growth mixtures in terms of particle size distribution and hydraulic conductivity using three different methods (i.e., constant head permeability, falling head permeability test, and tension infiltrometer test). The results were analyzed in relation to particle size distribution characteristics of the samples.

Table 1
Materials used for preparation of nursery mixtures.

Pine Island Mix	Nursery Mix	Greenhouse Mix	Costa Farms Mix
Hardwood Fines	Pine Bark (50%)	Pine Bark (37.5%)	Pine Bark
Pine Bark Fines	Sand (10%)	Sand (7.5%)	Sand
Eco-Soil	Coir Pith (40%)	Coir Pith (30%)	Coir Pith
Dolomite	Dolomite	Perlite (25%)	Dolomite
Talstar	Micro Mix	Dolomite	Styrofoam
Minors		Micro Mix	
TOC[a]: $72.1 \pm 6.9\%$	TOC: $69.7 \pm 7.4\%$	TOC: $43.8 \pm 4.7\%$	TOC: $60.5 \pm 11.7\%$

[a] TOC: total organic carbon.

2. Materials and methods

The samples of plant growth media were obtained from four different nurseries in Miami-Dade County in South Florida. These samples included Pine Island Mix, Nursery Mix, Greenhouse Mix and Costa Farms Mix. The general characteristics of the samples are presented in Table 1. The specifics of the mixture compositions were not available due to proprietary nature of the plant growth media used by the commercial nurseries. The plant growth mixes also have high organic content which is in contrast to regional soils which contain high percentages of clay, sand, loam and silt. The high organic content of the nursery mixtures is due to the efforts of the nursery operators to increase the moisture retention capacity of the plant growing media. The hydro-physical characterization of the mixtures included:

1. Sieve analyses using Fisher Scientific US Standard Sieve Series (ASTM E-11).
2. Constant head permeability tests using ELE International Permeameter (ASTM D5084).
3. Falling head permeability test using ELE International Permeameter (ASTM D2434).

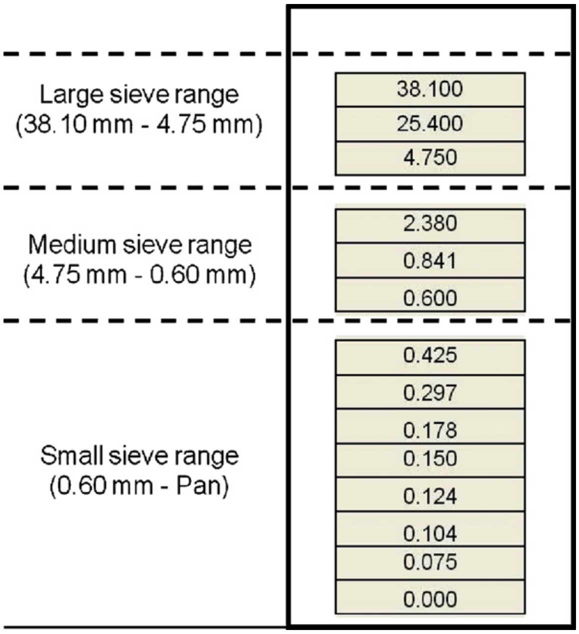

Fig. 2. Sieve sizes corresponding to large, medium, and small particle size ranges in samples used for permeability experiments.

4. Infiltration tests using Soil Measurement System Tension Infiltrometer.

Specific procedures followed for these tests are provided below.

2.1. Sieve analyses

Nursery sample mixtures were oven dried at 105 °C for 24 h. The samples were covered to avoid exposure to humidity in the laboratory and cooled to room temperature for 24 h. Each oven dried sample was sieved through a stack of 13 standard sieves ranging from 38.1 to 0.075 mm (ASTM E-11) as presented in Fig. 2. The duration of the sieving process was kept at 15 min for all samples. After 15 min at the shaker, the sieves were removed and the amount of material retained at each sieve was determined gravimetrically. The percent of material retained and passing through the sieves as well as the weight gain of the samples during sieve analysis were determined.

2.2. Hydraulic conductivity experiments

To characterize the hydraulic conductivity profile of the mixtures, each sample was divided into 3 different particle size ranges as shown in Fig. 3. The fractions in small sieve (0.425 mm–Pan), medium sieve (2–0.6 mm) and large sieve (38.1–4.75 mm) ranges as well as the entire mix were used to determine hydraulic conductivity profile of the samples.

Constant head permeability tests: The constant head permeability tests were conducted using an ELE International Permeameter Model EI25-0623 (Loveland, CO). This instrument consists of a transparent acrylic cylinder which holds the soil sample. The permeameter has two different openings, one at the top and the other at the bottom for continuous movement of fluid. To distribute the flow over the entire cross-sectional area of the permeameter, two porous stones were used at either ends of the cylinder. Since the flow of water through the media may cause actual movement of the soil particles or even the soil fragments, a spring was placed on the top porous stone to pack/contain the soil media movement. The constant head permeability test requires a constant flow of water through the medium; hence, a constant head supply device consisting of a large funnel with an overflow was placed over the permeameter. The sample was placed to about two-thirds full inside the permeameter sample compartment. The spring packing of the sample allows the calculation of the dry density as follows:

$$\rho_d = \frac{W}{AL}$$

where ρ_d is the dry density (g/cm^3); W is the weight of the specimen in the permeameter (g); L is the length of specimen (cm); and A is the area of specimen (cm^2) calculated as: $A = (\pi/4)D^2$; D is the diameter of specimen compartment (cm).

The hydraulic conductivity of the particular sample can be calculated by measuring the time and the constant head using the following equation:

$$K = \frac{QL}{Aht}$$

where K is the hydraulic conductivity (cm/s); Q is the volume (cm^3); t is the time of collection (s); and h is the head difference (cm).

Constant head permeability tests were performed six times. The data from two runs were used to estimate the dry density.

Falling head permeability tests: The falling head permeability test was conducted using the ELE International Permeameter, Model EI25-0623 (Loveland, CO). The equipment and assembly is similar to the constant head permeability; however, unlike the constant head supply device, the head was allowed to fall using a burette instead of the funnel assembly. The hydraulic conductivity of the sample can be calculated by the following equation:

$$K = \frac{aL\,\ln(h_1/h_2)}{At}$$

where a is the area of falling head test tube (cm^2); L is the final length of sample (cm); A is the area of sample chamber (cm^2); t is the falling head time from h_1 to h_2 (s); h_1 is the initial height (cm) and h_2 is the final height (cm).

Falling head permeability tests were repeated four times. Average of the measurements was calculated.

2.3. Infiltration tests

Tension infiltrometer measures the unsaturated hydraulic properties of the soil samples. Infiltration tests were conducted using a

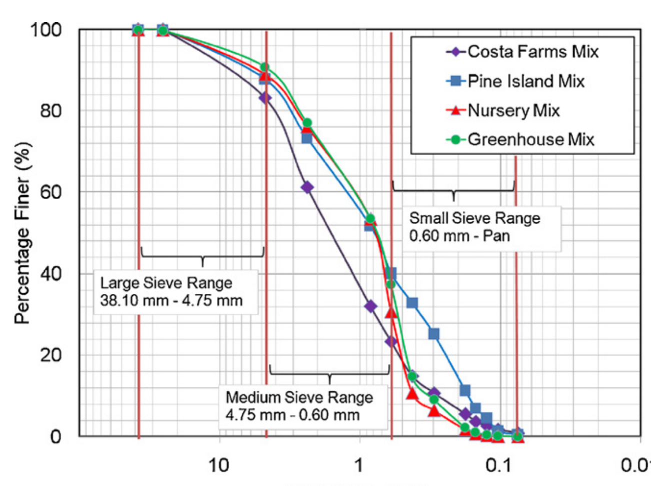

Fig. 3. Particle size distribution of the nursery mixtures.

tension infiltrometer by Soil Measurement Systems (SMS), Model SW-080B with a 20 cm base plate. During the infiltrometer tests, water was allowed to infiltrate the sample at a rate which is lower than the free fall rate of water through a column, which was accomplished by maintaining a negative pressure on the water. Since the tension infiltrometer measures the unsaturated hydraulic properties and the infiltration rate decreases as the sample becomes saturated until it attains a stabilized rate. The range of tensions attainable in the infiltrometer was between 0 and −30 cm water, and each cm corresponds to 1 mbar pressure. Therefore, at tensions close to zero, the infiltration rate is approximately equal to saturated hydraulic conductivity of the soil.

The saturated hydraulic properties of the soil can be calculated when similar infiltration experiments are performed at two different negative pressures. Experiments performed at different negative pressures (h) provide different volumes of water entering the soil per unit time (Q). This variation can be corrected using the

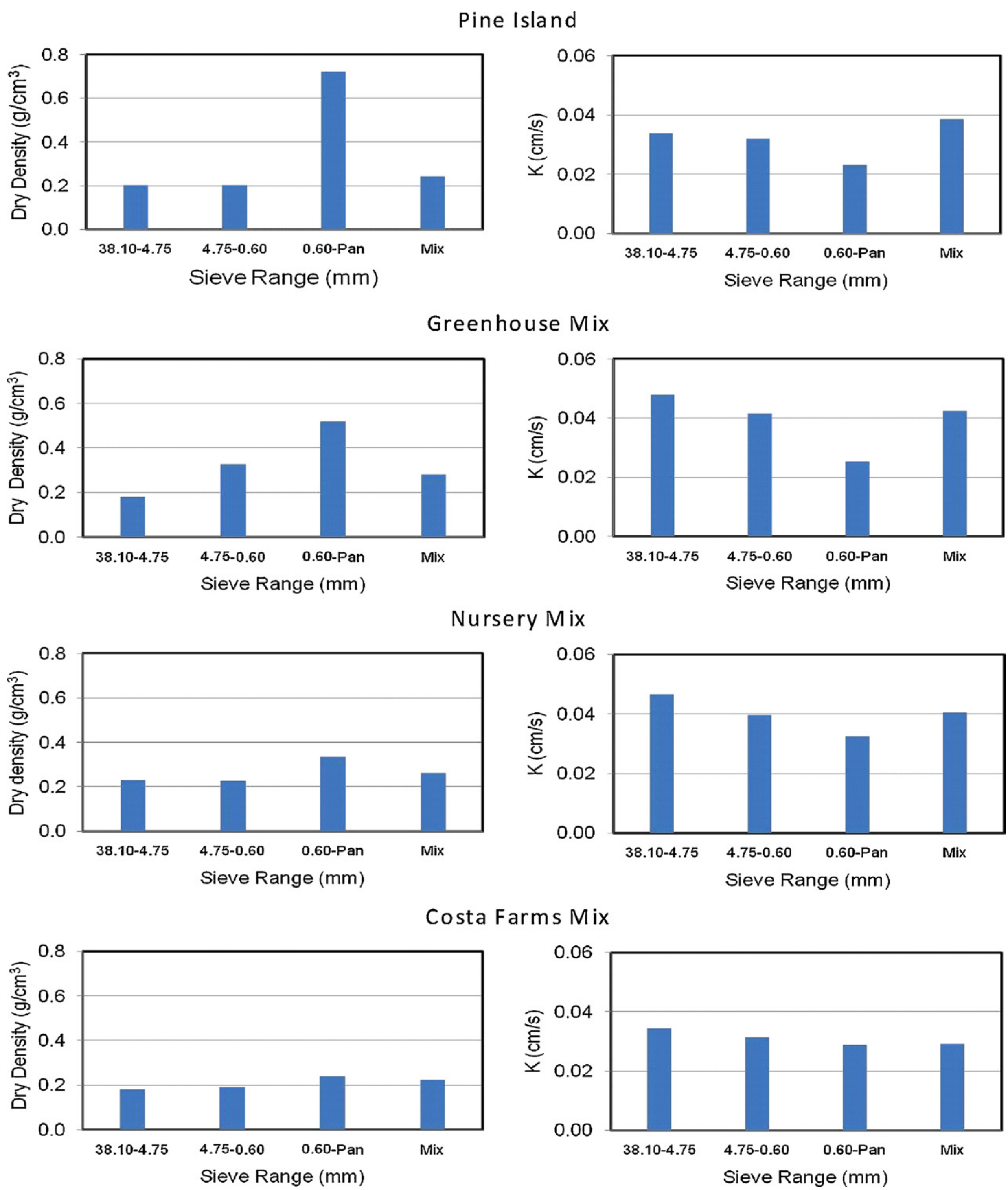

Fig. 4. Variation of dry density and the hydraulic conductivity in relation to particle size in nursery mixtures.

Table 2
Sieve analysis results of the nursery mixtures.

Sample	Initial soil mass (g)	Final soil mass (g)	Uniformity coefficient (Cu)	Gradation coefficient (Cc)	Weight change during sieving[a] (%)
Pine Island Mix	350.0	359.5	7.26	0.63	2.71
Nursery Mix	300.0	302.2	2.74	0.72	0.73
Greenhouse Mix	225.0	227.7	3.39	0.82	1.20
Costa Farms Mix	200.0	201.6	8.28	0.92	0.80

[a] During 20 min sieving time.

following correction factor:

$$\alpha = \frac{\ln[Q(h_2)/Q(h_1)]}{h_2 - h_1}$$

α is the correction coefficient (cm^{-1}); $Q(h_1)$ is the volume of water entering the soil per unit time (cm^3/h) at tension h_1; and $Q(h_2)$ is the volume of water entering the soil per unit time (cm^3/h) at tension h_2.

The hydraulic conductivity can be calculated as:

$$K(h) = K_{sat}\ \exp(\alpha h)$$

where $K(h)$ is the hydraulic conductivity. The volume of water entering the soil per unit time can be calculated as:

$$Q(h_x) = K(h)A$$

The volume of water entering the sample per unit time (cm^3/h) after correction can be calculated by the following equation:

$$Q(h_x) = \pi r^2 K_{sat}\ \exp(\alpha h_x)\left[1 + \frac{4}{\pi r \alpha}\right]$$

where $Q(h_x)$ is the volume of water entering the soil per unit time (cm^3/h); r is the inside radius of sample chamber (cm); K_{sat} is the hydraulic conductivity of saturated soil (cm/h); α is the correction coefficient (cm^{-1}); and h_x is the tension (cm).

Tension infiltrometer tests were performed four times with two pairs of negative pressure settings yielding two saturated hydraulic conductivity estimates.

2.4. Moisture retention capacity evaluation

The saturated water retention capacities of the samples were estimated using two different procedures. The first procedure consisted of adding water to the sample until it was saturated. For the second method, the sample was submerged in water until it was saturated. The amount of oven dried sample used for each experiment was 50 g. To prevent the intermixing and loss of the soil media, cheesecloth was used. The moisture retention capacity of the media was computed by accounting for the error due to the absorption of water by the cheesecloth as follows:

$$\text{Saturation water content}\quad (\%) = \frac{W - S - E}{S} \times 100$$

where W is the total weight of the saturated specimen (g); S is the weight of the soil sample (g); and E is the weight of cheesecloth (g).

Table 3
Water saturation characteristics of the nursery mixtures.

Sample	Water saturation by volume[a] (%)
Pine Island Mix	59.60 ± 4.60
Nursery Mix	64.40 ± 6.10
Greenhouse Mix	73.50 ± 1.30
Costa Farms Mix	71.00 ± 2.00

[a] Average of 3 tests.

Table 4
Dry density of the nursery mixtures.

Sample	Dry density (g/cm^3)
Pine Island Mix	0.28 ± 0.03
Nursery Mix	0.28 ± 0.02
Greenhouse Mix	0.31 ± 0.03
Costa Farms Mix	0.22 ± 0.00

3. Results

The plant growing media used by the nurseries contain amendments to satisfy the needs of the nurseries depending on their needs. One important need for nurseries is to increase moisture retention of the mixtures as much as possible. Hence, organic amendments (i.e., pine bark, manure) are used in addition to a small fraction of sand in preparation of the mixtures. Fig. 1 presents the particle size distribution of the nursery mixtures studied. All four mixtures had similar particle size distribution characteristics. However, the uniformity coefficient of the mixtures ranged from 2.738 to 8.276 as presented in Table 2.

Unlike the natural soils which tend to lose some mass during the sieving tests, the nursery mixtures showed increase in weight during analyses sieved fractions due to the highly organic nature of the samples. During the 20 min time interval from removing the sieved fractions out of the oven to measuring the individual sieve weights (15 min sieving and 5 min for weighing), a weight increase between 0.7% and 2.7% was observed due to absorption of moisture as presented in Table 2. The moisture retention capacity of the nursery mixtures was relatively high in comparison to that of natural soils. The water saturation characteristics of the nursery mixtures are presented in Table 3. The constant head permeability experiments provided the dry density and the hydraulic conductivity for each particle size range as well as the entire mixture. Table 4 presents the dry density of the nursery mixtures which ranged between 0.223 and 0.313 g/cm^3.

Table 5
Tension infiltrometer parameters and observations.

Sample	Negative pressure (cm)				Infiltration rate (cm/h)				Saturated hydraulic conductivity[a] (cm/h)
	$-h_1$	$-h_2$	$-h_3$	$-h_4$	h_1	h_2	h_3	h_4	
Pine Island Mix	154	40	100	55	6.1	32.0	15.1	27.7	0.18 ± 0.01
Nursery Mix	181	50	125	40	24.4	33.6	22.8	49.8	0.19 ± 0.04
Greenhouse Mix	153	40	100	44	23.6	36.4	17.4	29.4	0.40 ± 0.01
Costa Farms Mix	135	40	125	40	22.8	28.8	16.2	20.4	0.02 ± 0.00

[a] Average of two runs.

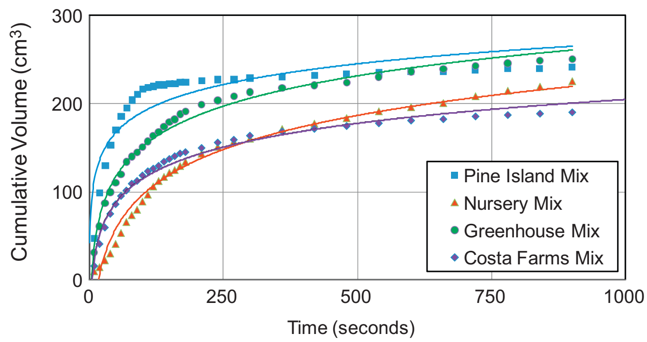

Fig. 5. Results from tension infiltrometer tests.

The variation of dry density and the hydraulic conductivity in relation to particle size for each mixture is shown in Fig. 4. Decrease in particle size results in an increase in dry density and decrease in hydraulic conductivity. The hydraulic conductivity of the mixture (mix) follows the particle size behavior which is prominent in the mix. For example the Pine Island sample had larger particle size; hence, the hydraulic conductivity is similar to the hydraulic conductivity of the sample corresponding to larger sieve range.

Tension infiltrometer was used to measure the unsaturated hydraulic properties of the nursery mixtures. To determine the saturated hydraulic conductivity, experiments were performed at two different negative pressures. Table 5 presents the conditions and saturated hydraulic conductivities measured by the tension infiltrometer. Fig. 5 presents the cumulative infiltration data as a function of time. Table 6 presents the equations which were fitted to the cumulative infiltration curves presented in Fig. 5.

The hydraulic conductivity of a saturated media as measured in the laboratory may vary with time, among the factors responsible for the variation have been cited the progressive deterioration of soil aggregation in the cations interaction between the soil and the flowing solution, and also the effects of the soil microorganisms and the changes in the volume of entrapped air (Poulovassilis, 1972). The hydraulic conductivity of a soil mixture depends on size and shape of the particles, void ratio, arrangement of the pores and particles, particle shape and orientation, properties of the pore fluid, and the amount of undissolved gas present in the pore water. The correlations developed for filtration conditions in porous media appear to apply with considerable accuracy to systems composed of rigid particles with relatively large sizes (0.3 mm and above); however, fail significantly when used to describe the permeability characteristics of media composed of small particles (of the order of 1 μm or less) (Michaels and Lin, 1954). The nursery mixtures consist of highly organic particles with their own porous structure. Hence, the filtration conditions are complicated due to retention of moisture within the particles in addition to voids between the particles.

Table 6
Equations fitted to the infiltrometer data (volume vs time).

Sample	Equation[a]	
Pine Island Mix	$y = 55.90\ln(x) - 161.2$	$R^2 = 0.974$
Nursery Mix	$y = 39.01\ln(x) - 65.14$	$R^2 = 0.981$
Green House Mix	$y = 49.81\ln(x) - 78.45$	$R^2 = 0.986$
Costa Farms Mix	$y = 33.92\ln(x) + 33.76$	$R^2 = 0.767$

[a] x is time (s) and y is cumulative volume (cm^3).

The saturated hydraulic conductivity of the nursery mixtures measured by constant head and falling head methods and saturated hydraulic conductivity measured by tension infiltrometer are presented in Table 7. The saturated hydraulic conductivity of the mixtures measured by constant head method ranged from 0.029 to 0.042 cm/s (104–151 cm/h) and by falling head method ranged from 0.078 to 0.112 cm/s (281–403 cm/h). The saturated hydraulic conductivity of the mixtures measured by tension infiltrometer ranged from 0.02 to 0.34 cm/h. Table 8 presents a comparison of the saturated hydraulic conductivity of the nursery mixtures measured by three methods with unconsolidated deposits. The saturated hydraulic conductivity of the nursery mixtures measured by the constant head permeability test indicate values similar to that of gravel and clean sand; values obtained by the falling head

Table 7
Saturated hydraulic conductivity of the nursery mixtures measured by three different test methods.

Sample	Constant head permeability test[a] (cm/h)	Falling head permeability test[b] (cm/h)	Tension infiltrometer permeability test[c] (cm/h)
Pine Island Mix	137 ± 22	382 ± 42	0.18 ± 0.01
Nursery Mix	151 ± 18	335 ± 23	0.19 ± 0.04
Greenhouse Mix	144 ± 6	281 ± 37	0.34 ± 0.01
Costa Farms Mix	104 ± 7	403 ± 18	0.02 ± 0.00

[a] Constant head permeability tests were performed six times. The data from two runs were used to estimate dry density.
[b] Falling head permeability tests were repeated four times.
[c] Tension infiltrometer tests were performed four times with two pairs of negative pressure settings.

Table 8
Comparison of the hydraulic conductivity of the nursery mixtures measured by different methods with unconsolidated soils.

Media	Saturated hydraulic conductivity (K) (m/yr)	Saturated hydraulic conductivity (K) (cm/h)
Unconsolidated deposits[a]		
Gravel	1×10^4–1×10^7	1.14×10^2–1.14×10^5
Clean sand	1×10^2–1×10^5	1.14–1.14×10^3
Silty sand	1–1×10^4	1.14×10^{-1}–1.14×10^2
Silt, loess	1×10^{-2}–1×10^2	1.14×10^{-4}–1.14
Glacial till	1×10^{-5}–1×10^1	1.14×10^{-7}–1.14×10^{-1}
Unweathered marine clay	1×10^{-5}–1×10^{-2}	1.14×10^{-7}–1.14×10^{-4}
Nursery mixtures used in this study		
Constant head test	9.1×10^3–1.3×10^4	104–151
Falling head test	2.4×10^4–3.5×10^4	281–403
Tension infiltrometer test	1.8×10^1–3.0×10^1	0.02–0.34

[a] *Source*: Freeze and Cherry (1979).

test were similar to that of gravel; and values obtained by tension infiltrometer were similar to that of clayey silt.

4. Conclusions

Hydro-physical characteristics such as water retention and hydraulic conductivity of four different nursery mixtures were characterized by laboratory experiments. Effect of particle size on hydraulic conductivity was analyzed after separating each sample by using three different size sieve sizes. Hydraulic conductivity measurements varied significantly between different test methods. The results of these types of characterization can provide a scientific basis for understanding of the non-point source water pollution from containerized horticultural and floricultural production systems and assist in the development of the best management practices (BMP) for operation of environmentally sustainable agricultural enterprises in South Florida. Understanding water retention and permeability characteristics of the nursery mixtures allows adjustment of application rates of water and agrochemicals so that runoff quantities are minimized.

References

Colangelo, D.J., Brand, M.H., 2001. Nitrate leaching beneath a containerized nursery crop receiving trickle or overhead irrigation. Journal of Environmental Quality 30, 1564–1574.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice Hall, Inc.

Michaels, A.S., Lin, C.S., 1954. Permeability of kaolinite. Industry and Engineering Chemistry 46, 38–45.

Ndiaye, B., Molenat, J., Hallaire, V., Gascuel, C., Hamon, Y., 2007. Effects of agricultural practices on hydraulic properties and water movement in soils in Brittany (France). Soil and Tillage Research 93 (2), 251–263.

Oklahoma Cooperative Extension Service Division of Agricultural Sciences and Natural Resources Oklahoma State University, 1998. Water Quality Handbook for Nurseries.

Poulovassilis, A., 1972. The changeability of the hydraulic conductivity of saturated soil samples. Soil Science 113 (2), 81–87.

Rao, N., Matthew, P.K., 1995. Effects of exchangeable cations on hydraulic conductivity of a marine clay. Clays and Clay Minerals 43 (4), 433–437.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76.

Ruth, B.E., 1946. Correlating filtration theory with practice. Industrial Engineering Chemistry 38, 564–571.

Savabi, M.R., 2001. Determining soil water characteristics for application of a hydrologic model in South Florida. Transactions of ASAE 44 (1), 59–70.

Savabi, M.R., Shinde, D., Konomi, K., Nkedi-Kizza, P., Jayachandran, K., 2005. Modeling the effect of soil amendments (composts) on water balance and water quality. Journal of Environmental Hydrology 13 (31), 1–14.

Savabi, M.R., Golobi, M.H., Abou-Arab, A.A., Kladivko, E.J., 2008. Effect of no-till farming on soil water intake. Journal of Environmental Hydrology 16 (21), 1–10.

US Army Corps of Engineers, Jacksonville District and South Florida Water Management District (SFWMD), 1999. Final integrated feasibility report and programmatic environmental impacts statement (PEIS). Everglades Comprehensive Plan, Section 5.

U.S. Environmental Protection Agency (USEPA). 1998. National Water Quality Inventory: 1996 Report to Congress. EPA841-R-97-008. U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC.

Whal, N.A., 2004. Effects of conventional and conservation tillage on soil hydraulic properties of a silty–loamy soil. Physics and Chemistry of the Earth: Parts A/B/C 29 (11–12), 821–829.

Wu, L., Vomocil, J.A., Childs, S.W., 1990. Pore size, particle size, aggregate size, and water retention. Soil Science Society of America Journal 54, 952–956.